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OF THE

NATIONAL SPELEOLOGICAL SOCIETY

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Contents

JULY 1972

NATIONAL SPELEOLOGICAL SOCIETY

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The Society serves as a central agency for the collection, preservation, and dissemination of information relating to speleology. It also seeks the preservation of the unique faunas, geological and mineralogical features, and natural beauty of caverns through an active conservation program.

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Underground Wilderness in the Guadalupe Escarpment

A Concept Applied

Robert R. Stitt [1] and William P. Bishop [2]

ABSTRACT

The concept of underground wilderness is not new to the discussion of protection of caves and karst features and has occurred regularly since before the Wilderness Act of 1964 became law. Those who have experienced the cave wilderness have never doubted its existence, but land managers have been slow to accept it. The definition of underground wilderness is discussed in terms of the value of the resource, its impact on an observer, and its defensible boundaries. The utility of the concept in management of the cave resource and the overlying lands is applied explicitly to the Guadalupe Escarpment of New Mexico and Texas. From the considerations of underground wilderness and its application to the Guadalupe Escarpment, concrete recommendations for underground wilderness in the Guadalupe Escarpment area are derived.

INTRODUCTION

In June, 1970, the National Speleological Society (NSS) presented to the National Park Service (NPS) and the United States Forest Service (USFS) a proposal for a Guadalupe Escarpment Wilderness Area (NSS, 1970), to be made up of the major portions of Carlsbad Caverns National Park in New Mexico, Guadalupe Mountains National Park in Texas, and the southern section of the Lincoln National Forest between the two parks. This proposed wilderness area contains one of the world's major cave-bearing limestone areas—the Guadalupe Reef Complex of Permian Age.

Since that time, both the NPS and the USFS have made management proposals for this area which have included proposals for wilderness designation or the establishment of wilderness study areas (NPS 1971b, 1971c; USFS, 1971). The surface protection provided by these government proposals has not proven to be adequate for protection of the cave resources; thus further discussion is necessary.

The natural beauty of caves has been experienced by countless thousands of persons who have been attracted to developed caves such as Carlsbad Caverns. A smaller number of persons have enjoyed the wilderness experience in caves. The extension of modern civilization and its effects has made preservation of some of the remaining wilderness heritage, including caves in a natural state, even more desirable. The Guadalupe Escarpment with its many outstanding caves of national significance presents an important opportunity to preserve an entire karst area intact for the enjoyment of future generations of Americans.

That caves are an important part of the natural heritage which is in vital need of protection has not been disputed. The relatively long periods of time (thousands of

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years) necessary for the recovery of a cave system from human effects, including vandalism and unwise development, make protection for caves even more important than protection for some surface features that may recover from upsets in only a few decades or centuries (de Saussure, 1962).

There are two ways in which the wilderness concept can be applied to caves. One is through the inclusion of surface areas overlying caves in the National Wilderness Preservation System (which would by inference include the caves as wilderness). The other is the inclusion of caves alone as underground wilderness—the concept to be discussed in this document. Surface wilderness protection, where it is applicable, has two main advantages: it assures the proper management of surface areas overlying the caves in a manner compatible with underground wilderness preservation, and it decreases the accessibility of the caves by limiting surface travel to wilderness means. In cave areas where surface wilderness is not possible, however, the concept of underground wilderness, coupled with beneficial surface management, can be used to preserve the wilderness values of caves and karst. Because the surface and underground environments in karst areas are complexly and vitally interrelated, planning for use of either must take into consideration the other.

The concept of underground wilderness has been discussed previously, notably in the NSS proposal for wilderness in Mammoth Cave National Park (NSS, 1967), in a wilderness resource survey of Mammoth Cave National Park published by the Cave Research Foundation (Davidson and Bishop, 1971), and most recently by Watson and Smith (1971). The present discussion applies the underground wilderness concept explicitly to the caves of the Guadalupe Escarpment.

THE NEED FOR UNDERGROUND WILDERNESS

There is a twofold need for underground wilderness in the Guadalupe Escarpment—to provide protection for the delicate underground resources and to set managerial guidelines to be used in the administration of these resources. Underground wilderness protection will be of the highest value in areas not protected by surface wilderness status and in caves near the boundaries of surface wilderness preserves which are readily accessible from nearby roads. The designation of underground wilderness serves a useful function in meeting both of the above needs, regardless of the designation of the surface lands.

The more than 300 known caves of the Guadalupe Escarpment contain many irreplaceable features, including unusual examples of phreatic cave development (Bretz, 1949; Thrailkill, 1965) and unique and varied cave minerals and speleothems (see, for example, Black, 1956). An upset of any of the delicately balanced biological, mineralogical, hydrological, or climatological parameters of the cave/surface aggregate could prove disastrous to these unique features (Cave Cons. Assoc., 1971; Poulson and White, 1969). On the time scale of the lives of individual human beings, caves are not a renewable resource. Therefore, the protection of underground resources is necessary and desirable to assure the preservation of unique recreational, scientific, and aesthetic values (Fig. 1). The Guadalupe Escarpment area presents a significant opportunity for preservation of underground resources for recreational and research purposes.

Application of the concept of underground wilderness to the Guadalupe Escarpment can be used to set long term management guidelines for preservation of caves and other karst features. Thus the wilderness concept can be considered a management tool to aid administrators in the NPS and USFS in achieving their goals. The complex inter-relations between the surface and underground environments in a karst area dictate that management policies must consider the entire environment—underground as well as surface—and thus the concept of underground wilderness to supplement surface wilderness is important.

Figure 1. A delicate underground wilderness in need of protection (photo by Pete Lindsley).

The limited nature and the need for careful management of the wilderness resource in this nation have been the subject of conferences and studies for some years (see, for example, Anon., 1962; Schwartz, 1969). Wilderness is unquestionably a natural resource and is, therefore, something which human beings can use. Because it is a limited resource, it must be managed with care and protected in order that he maximum benefit may be derived from it. Even though a resource may not be easily accessible, it is still a resource to be protected and utilized for human benefit. In planning for the use of some resources, a provision for future discovery must be included, for instance mineral resources which are now only suspected.

A karst area is also a resource, both known and suspected. In a karst area, pollution may spread unseen through the groundwater and thus have a harmful effect on humans. The underground aquifers in a karst may bring water from distant watersheds to areas of heavy use by humans. Also, the caves of the karst have aesthetic, recreational, and scientific uses which make them a valuable asset. Even though the caves in a karst area might not have been discovered or visited, they and the rock that contains them still represent a resource which needs to be managed.

The best management for a karst area such as the Guadalupe Escarpment would provide "multi-level" management guidelines to assure that the surface and underground environments were managed in total harmony with one another. Just as the concept of surface wilderness is an important management tool for surface resources, so emphatically is the concept of underground wilderness important for management of the underground resources. The designation of any natural resource as wilderness is a clear statement of objectives for the management of that resource, and it is an enforceable statement of those objectives. Thus, because of the interrelationships between the surface and underground in a karst, the concepts of surface and underground wilderness must complement each other.

THE CONCEPT OF UNDERGROUND WILDERNESS

The Wilderness Act of 1964 has established certain criteria for the inclusion of an area in the National Wilderness Preservation System; it is to be composed of "federally owned areas . . . to be administered for the use and enjoyment of the American people in such a manner as will leave them unimpaired for future use and enjoyment as wilderness. . . ." The Act further sets forth the reasons of Congress for establishing such a system: "to assure that an increasing population, accompanied by expanding settlement and growing mechanization, does not occupy or modify all areas within the United States and its possessions, leaving no lands designated for preservation and protection in their natural condition. . . ." From these paragraphs, the intent of Congress was to secure "areas" and not only lands, and the Wilderness Act can thus apply to such features as caves, as well as mountains, forests, and seashores.

The Act goes on to define a wilderness more specifically:

> A wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain. An area of wilderness is further defined to mean in this chapter an area of undeveloped Federal land retaining its primeval character and influence, without permanent improvements or human habitation, which is protected and managed so as to preserve its natural conditions and which (1) generally appears to have been affected primarily by the forces of nature, with the imprint of man's work substantially unnoticeable; (2) has outstanding opportunities for solitude or a primitive and unconfined type of recreation; (3) has at least five thousand acres of land or is of sufficient size as to make practicable its preservation and use in an unimpaired condition; and (4) may also contain ecological, geological, or other features of scientific, educational, scenic, or historical value.

Caves on Federal land can clearly meet the requirements of the Wilderness Act under items 1, 2, and 4 and by proper gating and access control may meet the requirements of item 3 for "practicable . . . preservation and use in an unimpaired condition." Wild caves, including most of those in the Guadalupe Escarpment, certainly retain a primeval character and influence, and those caves which have not been "improved" by the works of man are of "wilderness" nature as defined by the Wilderness Act.

Beyond the physical aspects of wilderness which are met by the caves of the Guadalupe Escarpment, implicit in the definition in the Act is the requirement that wilderness must affect an observer in a particular way. Watson and Smith (1971) use this requirement to formulate a further definition of wilderness:

> "*Wilderness*" is land that can provide man with wilderness experience.
>
> This definition is not circular, for wilderness experience can be defined as follows:
>
> *Wilderness experience* consists of feelings of aesthetic appreciation, of self-reliance, and of remoteness from the ordinary activities and works of man.

Underground wilderness can and does provide a "wilderness experience" (Fig. 2) and fully meets this requirement of the definition of wilderness.

Underground wilderness must have, therefore, three qualities—a value (scenic, scientific, etc.), an impact on the observer (the wilderness experience), and defensible boundaries. Land planners in the past have usually considered only horizontal boundaries in determining best usage of the Earth's resources, but in fact, humankind has conquered the planet in three directions. Humans have soared through the air and penetrated below the surface of both the oceans and the Earth, as well as extended their hegemony over the surface. Land planners place boundaries between areas of divergent uses; towns have zoning laws, and forest planners often set aside some areas for special uses and others for multiple uses. Thus wilderness may be adjacent to developed areas. It is not only consistent with past practices of land management and planning, but necessary, as we recognize the effects of humankind upon the entirety of the planet, that we consider both vertical and horizontal boundaries in planning for the use of our three-dimensional resources.

Precedent has been set in other areas for the concept of vertical boundaries. Proposals have been made for undersea wilderness in seashore parks with surface use not unduly restricted. Motorboats can cruise above a pristine and preserved seafloor wilderness

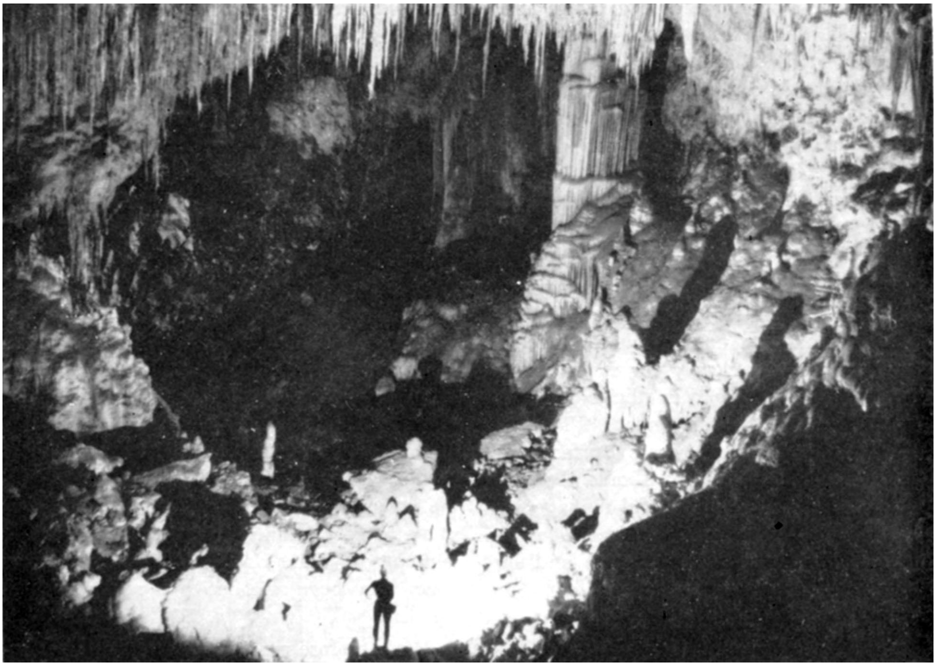

Figure 2. Wilderness experienced beneath the earth (photo by Alan Hill).

(given control of engine effluents and noise). Airplanes fly freely over almost all land areas, including most of those set aside for surface wilderness protection. Surface land rights are often separated from underground rights; mineral rights are often sold separately from rights to grazing or other surface usage. Entire cities have been built over hills riddled with mine tunnels. Natural gas has been stored in porous rock layers underlying farms and pastures, and oil is found underlying surface areas used for any normal surface use.

Thus the concept of use separation by vertical boundaries is not new, but the dimension circumscribed by the boundaries is different from that usually applied to land planning. The classical two-dimensional approach to land planning must be superseded by a three-dimensional approach if the need for fuller utilization of resources is to be met. Imaginative land planning in the last third of the Twentieth Century must take into account all aspects and dimensions, transcending the limited and arbitrary methods of the past which are no longer adequate for our rapidly progressing technological society.

Underground wilderness we define, then, as that portion of a cave or karst area, lying below the surface of the earth, which meets the requirements of the Wilderness Act regarding value and impact on the observer. Boundaries of an underground wilderness area can be determined in either of two ways: first, by defining surface boundaries and projecting them below the ground (surface definition) and second, by setting aside a particular portion of a cave as defined by its physical boundaries, such as a particular passage or the area enclosed by certain boundaries (underground definition).

The size of an underground wilderness area would be governed by the second part of the Wilderness Act size-limitation clause—". . . of sufficient size as to make practicable its preservation and use in an unimpaired condition." Although surface areas designated above underground wilderness might be larger than 5,000 acres, size alone is neither a necessary nor desirable factor, since the installation of a gate would make practicable unimpaired preservation and use of any cave.

The simplest management situation, of course, would be to couple underground wilderness with surface wilderness and treat the area as a unified whole. This has been proposed previously for much of the Guadalupe Escarpment in the NSS document *Guadalupe Escarpment Wilderness* (1970). But in some cases surface and underground management should be considered separately. The careful management of surface use in a non-wilderness fashion can make underground wilderness and surface non-wilderness uses compatible.

Underground wilderness designated by the surface concept would normally commence at the surface of the ground and would comprise a large block of rock that contains voids which are both known and unknown wild caves; water both above and below the water table; and the atmosphere, formations, and biota of the caves. The block could be limited if necessary to the volume between certain elevations if protection of cave passages below a developed portion of a cave were desired. The underground definition, on the other hand, would be implemented by designating as underground wilderness a particular passage or portion of a cave as defined by its known physical boundaries. Obviously the surface definition has a major advantage over the underground definition, in that it would protect presently unknown caves in the block. In some instances use of both the surface and underground definitions might be desirable. For the protection of a wild section of a developed cave, a gate might be installed in a particular passage and the block behind it designated as underground wilderness (with boundaries defined on the surface above). The application of the wilderness concept to a particular area or block need not interfere with non-wilderness use even in an adjacent passage, provided that reasonable precautions are instituted to eliminate or reduce possible undesirable interactions.

In the underground wilderness area, of course, all of the uses of wilderness are possible, and all of the qualifications and prohibitions of the Wilderness Act apply. Man-made "improvements" such as permanent lights, built-up trails, ladders, or similar devices would not be permitted. Mechanized "vehicles" such as elevators would be forbidden. Visitors entering the area would be allowed only equipment and methods consistent with assuring that the wilderness quality of the cave would not be compromised. Visits would probably have to be carefully controlled, because the amount of unrestricted traffic a wilderness cave can bear without being damaged is small.

We therefore propose underground wilderness as a concept that, when implemented, will permit management of different levels or layers of an area for differing uses, while taking into consideration the interactions between those levels. Although this concept could be used as a supplement to existing practices, it is probably more important as a concept on its own, since it makes clear the intent of management programs, and clearly defines not only the goals of management but the means by which these goals are to be achieved. Thus, the underground wilderness concept is important not only to the preservation of the caves in a wild state, but to the clear definition of this goal and to the management policies necessary to achieve it.

UNDERGROUND WILDERNESS IN THE GUADALUPE ESCARPMENT

According to NSS records, the Guadalupe Escarpment, from the eastern boundaries of Carlsbad Caverns National Park to its southern extremity in Guadalupe Mountains National Park, contains more than 300 known caves—including many of national

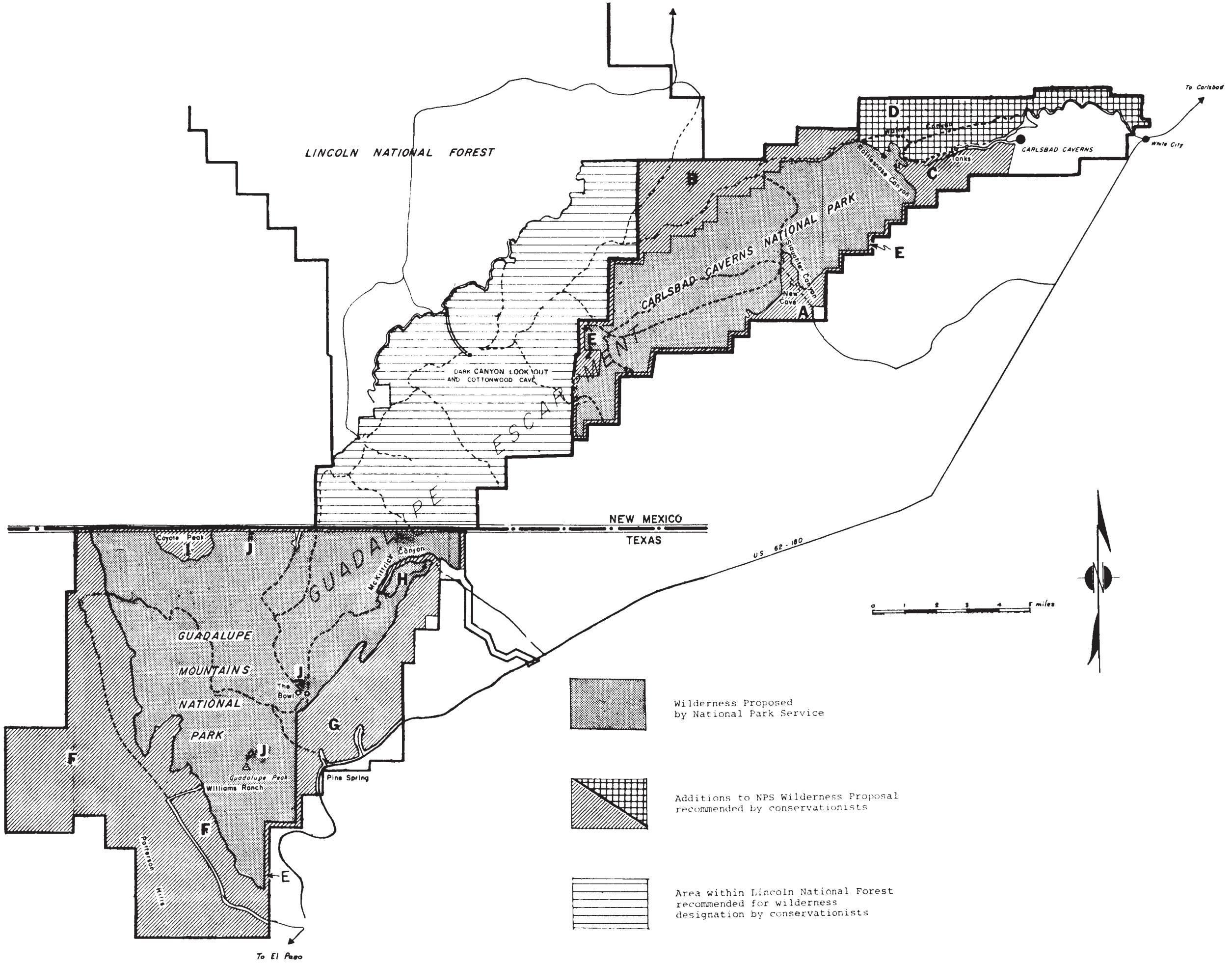

Figure 3. The proposed Guadalupe Escarpment Wilderness (from the joint announcement by the Wilderness Society and the Sierra Club, 1971).

significance—ranging in size from Carlsbad Caverns to small rock shelters containing traces of the Indians who once ranged this section of the country. Most of these caves are presently in a wilderness state (the developed portion of Carlsbad Caverns is the major exception), although vandalism is evident in some places even to the casual observer. Because of the size of this area, its relative inaccessibility due to the wilderness nature of its surface, and the abundance of limestone making up the Guadalupe Reef complex, there is excellent reason to believe that there are many other caves awaiting discovery—and many known caves probably contain yet-to-be discovered passage. Protection of the wilderness character of the Escarpment must take these facts into account.

The NSS (1970) and other organizations (Anon., 1971) have proposed that the portion of the Guadalupe Escarpment area containing the bulk of the caves be included in the National Wilderness Preservation System as a conventional surface wilderness area (Fig. 3). This designation is necessary to ensure protection of the underground resources as well as of the many and valuable surface wilderness features. The NPS has made proposals for wilderness designation for portions of the primitive karst areas in the two national parks (1971b, 1971c)*, and the USFS has proposed a wilderness study area for the part of the Escarpment lying on USFS lands between the two parks (1971). Surface wilderness protection should be extended to all of the eligible lands in the Escarpment; but wilderness caves, including those in areas not qualifying for surface wilderness designation, should also have the protection of the Wilderness Act.

The only means of *de jure* wilderness protection for caves below surface areas not eligible for wilderness designation or caves isolated from surface features worthy of protection is designation as underground wilderness. Because most of the caves in the Guadalupe Escarpment are, in their own right, eligible for and worthy of wilderness protection, the concept of underground wilderness should be applied to them.

Carlsbad Caverns National Park

In Carlsbad Caverns National Park, there are at least 12 known caves that lie outside of the NPS-proposed wilderness which should all be afforded underground wilderness protection. In the eastern portion of the park, there are four caves, in the Slaughter Canyon area seven, and in the northwest corner, at least one. These caves have not been included in proposed surface wilderness areas because of planned surface use of a nonwilderness nature, but with careful planning of surface use there is no reason why the concept of underground wilderness cannot be used to protect all of these caves and others yet to be discovered by a designation of much of the park as underground wilderness. In addition, Carlsbad Caverns itself contains many areas that are eligible for underground wilderness protection. With proper consideration given to future plans for development and use, certain areas of the Caverns could be designated as underground wilderness and used as such.

Lincoln National Forest

In *Southern Guadalupe Management Area* (USFS, 1971), the USFS presents a detailed preliminary inventory of wilderness resources in the southern part of the Guadalupe district of Lincoln National Forest. One finding of this study is that the surface of certain areas that contain a high potential for cave discovery may not meet present Forest Service standards for inclusion in the National Wilderness Preservation System. While this conclusion may be debated, it underscores the need for and the applicability of underground wilderness designation for the caves of the area. These caves can and should be included in the system as underground wilderness.

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* Editors' Note: While this paper was in press, President Nixon presented a wilderness message to Congress which included wilderness recommendations for both these parks. These more recent views of the NPS are now available from the Park Service.

While surface wilderness protection is desirable for a large part of the USFS lands, USFS management proposals for the surface area to the north of Guadalupe Ridge would generally be compatible with underground wilderness management for the caves contained therein even without surface wilderness designation. The presence of limited-use jeep trails (although they complicate management by making access easier) and low-impact surface developments, such as lookout towers and electronics sites, will not seriously compromise the quality of underground wilderness *if* proper management precautions are taken.

Underground wilderness designation, then, should be applied to caves in four areas of the Guadalupe Escarpment: to caves or portions of caves lying outside the boundaries of surface wilderness in the national parks; to caves near the boundaries of surface wilderness which may need additional protection; to caves in the Lincoln National Forest lying outside the surface wilderness area; and to caves in areas not necessarily deserving of surface protection. Finally all of the caves of the Escarpment which meet the qualification of the Wilderness Act should also be protected.

The Uses of Underground Wilderness

Underground wilderness can be used for three purposes: recreation, as a baseline for management decisions, and as a laboratory for basic and applied research. For a more detailed discussion of usage than can be included here, the reader is directed to the Cave Research Foundation's study *Wilderness Resources in Mammoth Cave National Park* (Davidson and Bishop, 1971).

The use of underground wilderness of most interest to the public is recreation—to obtain the wilderness experience (Fig. 4). Although many persons prefer the more "civilized" approach to caves of the lighted, paved trail and the elevator to the surface at trip's end, there is a growing body of persons in the United States who are interested in obtaining more from a cave visit than a talk given by a guide. They prefer a more natural, wild caving experience where they may pit their skills against the cave in its primitive, solitary state. In New Mexico alone, we estimate that there are more than 1,000 persons who have enjoyed the experience of wilderness caving, and the number in Texas is probably at least three to five times larger. Because the Guadalupe Escarpment caves are widely known throughout the United States, the potential number of recreational visitors seeking a wilderness experience is quite large. Only a small percentage of these wilderness cavers are members of conservation-oriented organizations such as the NSS. As industrialized, urban society becomes more complex, the number of people interested in renewing themselves by a return to Nature, temporary though it may be, will grow larger.

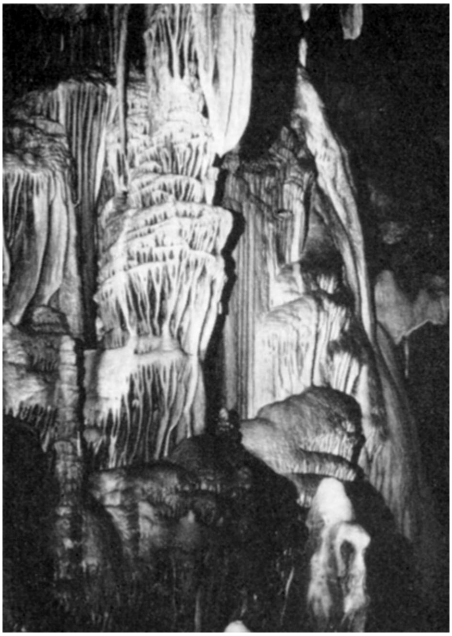

Figure 4. Underground wilderness (photo by W. P. Bishop).

Thus there will be an increased need for recreational services and facilities to serve a growing body of wilderness seekers. One of the places where this need can be met best is in the National Parks and National Forests, where land planners have had enough foresight to set aside some natural resources for the use and enjoyment of future generations. A management plan for the National Parks and Forests, then, must take into account the increased demands for wilderness experience, balance these demands with policies for maximum preservation of the resources, and allow use consistent with both goals.

Because the fragility of the underground resources does not allow unlimited recreation in wilderness caves without threatening the wilderness values, the concept of guided wilderness caving has been proposed by many [including the NSS (1970) and the NPS (1971a)] as a means of increasing the opportunity for underground wilderness recreation while presenting minimum opportunities to damage the resources. Guided wilderness caving will extend the opportunity for underground wilderness recreation in the Escarpment to many people.

The National Park System and the National Wilderness Preservation System are rapidly becoming islands of "naturalness" surrounded by the ever-encroaching, harmful, environmental effects of man. Different visitation policies will certainly have different effects upon the environment. Thus, to meet the requirement in its charter to maintain its lands in a natural state, the NPS will need a baseline against which to judge its management policies—a baseline against which to judge the effects of man's use of its lands. Wilderness provides that baseline.

While maintenance of an area completely unaffected by the forces of man is, of course, impossible, proper management can minimize such effects. And so, the effects of visits to Carlsbad Caverns can be determined from comparison of the conditions there with those in a wilderness cave in the area. The question, "What would Carlsbad Caverns be like if . . .?", will have an answer as knowledge of pristine caves increases.

The experience of many karst researchers (see, for example, Poulson and White, 1969) has led to two conclusions: caves and karst represent some fairly unique research opportunities, and for many cave research programs to be meaningful the caves must be relatively undisturbed. The Guadalupe Escarpment is one of the few major karst areas in the United States entirely on Federal land, and yet it is of an entirely different nature from the one other largely federally-owned area of equivalent potential—Mammoth Cave National Park and the Central Kentucky Karst in Kentucky. Differences in climate and geological conditions are so great that entirely different bodies of knowledge are to be gained from study of the two areas, and important comparisons are to be drawn. This great research potential must be recognized, and measures must be taken to protect the natural features so that here will remain an environment uninfluenced by the adverse effects of man in which research may be carried out.

Plans for cave use in the Guadalupe Escarpment must take into account all potential uses of underground wilderness: recreation, management and interpretive baselines, and scientific research. Only through a balanced, well-thought-out program of management can caves be used in a manner consistent with the goal of preserving wilderness. We propose that underground wilderness designation for the caves of the Guadalupe Escarpment is an important aspect of that planning.

RECOMMENDATIONS

We make the following recommendations for the application of the underground wilderness concept to the Guadalupe Escarpment:

(1) As much of the Escarpment area as possible should be afforded surface wilderness protection by inclusion in the National Wilderness Preservation System.

(2) All caves in the Escarpment area, whether lying under wilderness lands or under lands not eligible for surface wilderness protection, should be given under-

ground wilderness protection by the designation of surface and/or underground boundaries under the Wilderness Act.

(3) Pending the completion of detailed wilderness studies and proposals that consider both the underground and surface wilderness potential of the Escarpment, the entire Escarpment should be managed as a *de facto* wilderness, in such a fashion that the wilderness values are preserved.

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Dynamics of a Sinking Stream System: Onesquethaw Cave, New York

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ABSTRACT

Onesquethaw Cave, in Albany County, New York, has formed as the direct result of the subsurface diversion of a perennial surface stream. Throughout its history the cave has been subject to severe flooding by storm runoff, which has contributed much to its growth and to the development of a distinctive braided passage pattern. Runoff from a single storm is capable of producing dramatic erosional, solutional, and depositional changes. Where the geologic setting is simple, with continuous bedding-plane partings, the cave exhibits graded passages concordant to the bedding structure, but in areas of heterogeneous lithology and structural deformation the cave is complex, ungraded, and discordant to the structure, with numerous diversion passages formed by invading floodwaters. The diverse geologic setting has produced great variations in hydraulic efficiency within the active passages, with the result that floodwater is allowed to pond behind passage constrictions and create abnormally steep hydraulic gradients within the limestone. Under these circumstances, maze passages and blind tubes are rapidly developed above the normal low-flow level of the phreatic zone by the turbulent, solutionally aggressive floodwater. The underground courses of sinking streams, often considered simple in plan and development, actually can involve the most complex flow dynamics and conduit geometry of any groundwater setting.

INTRODUCTION

This paper is an interpretation of a single cave system, not as an isolated geomorphic feature, but as a representative of the entire genetic class of caves that owe their origin to the diversion of a perennial surface stream to an underground route. Caves of this type are formed where water is accumulated in the surface headwaters of a sinking stream in quantities sufficient to provide a single continuous but highly variable source of recharge to the cave at the point of subsurface diversion. Because much, if not most, of the resulting cave development is associated with the high rates of groundwater flow produced by storms, such caves may be classified as *floodwater caves.*

Onesquethaw Cave, in Albany County, New York, is fed by a sinking stream draining 1.3 square miles that is capable of flooding the entire cave to the ceiling during any month of the year. Although in this regard it is typical of many floodwater caves, this cave is worthy of special attention because of the complexity of its geologic setting and subsurface flow.

The purpose of this investigation was to determine some of the groundwater flow regimes, solutional and depositional features,

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and cave patterns that characterize floodwater cave development and to illustrate the surprising variety of these characteristics in spite of what appears at first glance to be the simplest form of karst drainage. To obtain quantitative field data, Onesquethaw Cave and its resurgence route, Jordan Cave, were mapped with detailed reference to their geologic and hydrologic setting. The horizontal component of the survey was conducted with a mounted forester's compass and fiberglass tape, with a maximum error of approximately 0.5%; the vertical component was surveyed with a U-tube manometer, or "level tube" (Palmer, 1970), with a maximum error of approximately 0.02%. Special care was taken in the vertical survey to obtain precise measurements of water levels, passage gradients, and variations in geologic structure. The resulting map and profile are shown on the accompanying plate (in rear pocket).

GEOLOGIC SETTING

The Onesquethaw Cave system is located in the Onondaga Limestone of Middle Devonian age, which is exposed at the northeastern edge of the Helderberg plateau in a narrow structural bench overlooking the Mohawk-Hudson lowlands (Fig. 1). The area lies at the western border of Appalachian deformation, where the gentle

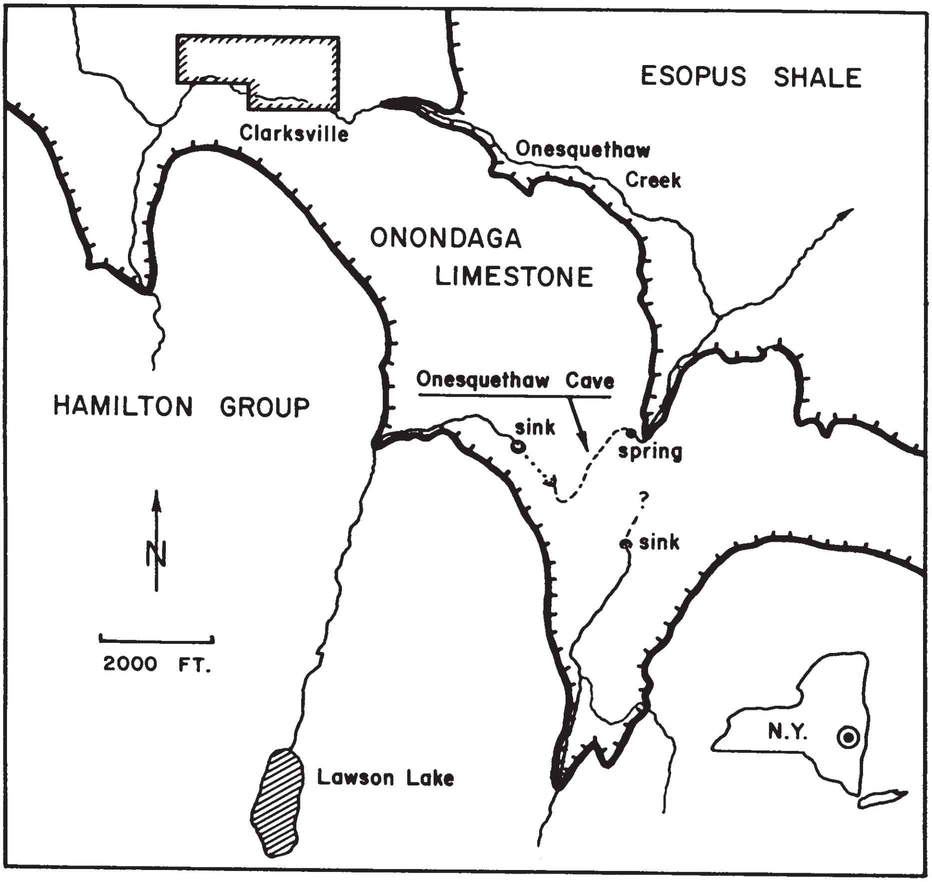

Figure 1. Location and geologic setting of the Onesquethaw Cave system.

southwesterly regional dip characteristic of the plateau is disrupted by numerous faults and low-amplitude folds. The geology of this region, including its correlation with formations in other nearby physiographic provinces, has been discussed in detail by Ruedemann (1930).

The Onondaga Limestone in Albany County is a crystalline limestone from 85 to 100 ft thick, containing abundant but discontinuous chert beds and zones of chert nodules. The limestone is underlain by the Esopus Shale and overlain by shales and sandstones of the lower Hamilton Group (Fig. 2). The basal Onondaga beds comprise a resistant, limy sandstone (Schoharie Formation) that forms a prominent northeast-facing escarpment overlooking a deep gorge cut in the Esopus Shale by Onesquethaw Creek. The resistance of the sandstone to weathering appears to be the main factor responsible for the prominence of the karsted limestone bench, although the insoluble chert beds may be of local importance in this respect. On the southwest, the strip of limestone is bordered by steep hills, composed of the overlying Hamilton beds, that rise to an average height of 500 ft above the limestone surface. Although the limestone is masked by glacial till in many places, sinkholes and swallow holes are abundant in local areas where the till is thin or absent, and well-developed karren topography dominates the up-dip edges of the limestone bench. Most of the streams that flow from the shaly hills onto the limestone plain disappear underground near the shale-limestone contact, forming small but intricate caves.

The Onesquethaw system is the largest of these caves, containing roughly one mile of mapped passages in a linear pattern interlaced with complex diversion routes on several levels. In its erratic history of flow, the underground stream responsible for the development of the cave has encountered an unusual variety of geologic conditions (see Fig. 3). From southwest to northeast, the cave passages intersect relatively pure limestone with prominent bedding-plane partings and joints, pass downward through a zone of interbedded chert and limestone which includes thirteen distinct chert beds, and finally extend laterally along the strata into a relatively chert-free zone typified by strong bedding-plane control of passage development. In terms of geologic structure, the passages encounter an area of gentle dip (2.5 degrees to the southeast), a reverse fault with associated joint swarms and gash

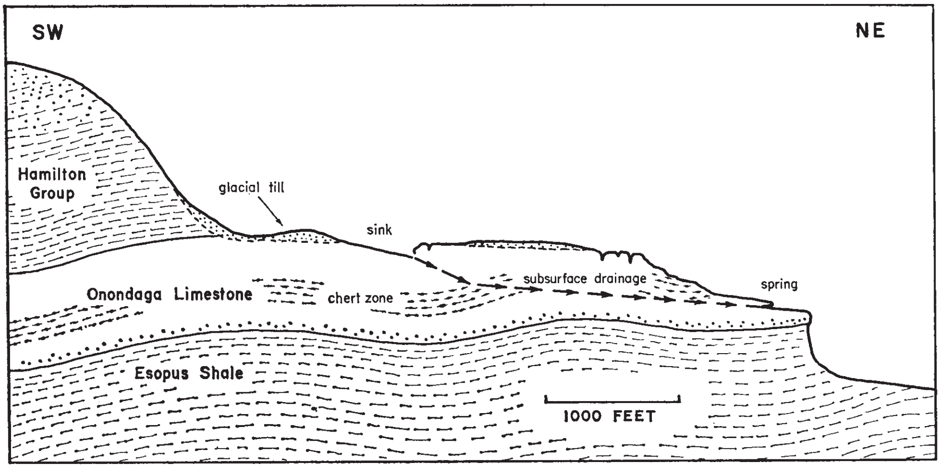

Figure 2. Generalized geologic cross section through the bench of Onondaga Limestone in the vicinity of Onesquethaw Cave.

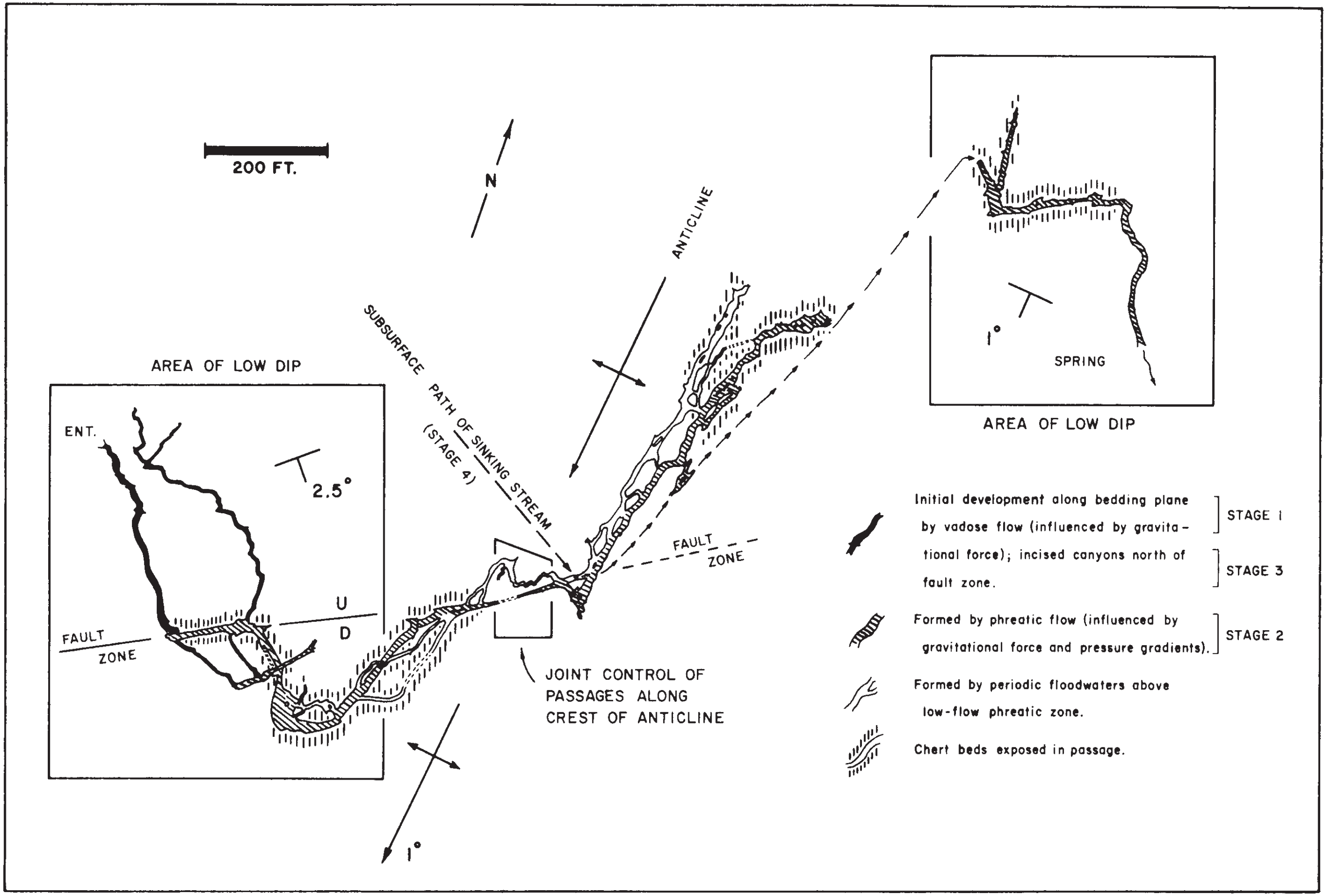

Figure 3. Geologic and hydrologic character of passages in the Onesquethaw Cave system.

veins of calcite, both limbs and the axis of a plunging anticline, and four joint sets resulting from regional shear stress and from tension along the crest of the anticline.

HYDROLOGIC SETTING

Hydrologic Definitions

The complex geologic setting of Onesquethaw Cave results in an equally complex pattern and history of groundwater flow, an adequate account of which requires precise definitions of several commonly used but often mis-applied hydrologic terms. Because the essence of karst hydrology is the determination of subsurface flow paths and the interpretation of the solution channels formed along such paths, the forces that control the movement within each groundwater zone must be understood.

Flow within the *vadose zone,* in which the bulk of the limestone formation is not saturated by groundwater, takes place mainly in response to gravitational force. Significant deflections from a vertical, downward flow direction are caused only by variations in the availability and geometry of openings such as joints, bedding-plane partings, and faults. Because water pressure does not exceed one atmosphere throughout this zone, flow paths are essentially independent of pressure differences. Movement of water along a non-vertical opening, such as an inclined bedding-plane parting, will tend to have a strong down-dip orientation, with only minor deviations imposed by local structural conditions and varied parting width.

In contrast, within the underlying *phreatic zone,* in which essentially all openings are filled with water under pressures greater than one atmosphere, flow is governed both by gravitational force and by differences in hydrostatic pressure. The downward increase of pressure in this zone offsets to varying degrees the influence of gravity in determining flow directions. Differences in elevation between the highest points in the phreatic zone and the spring outlets create a hydraulic potential that allows water to move, however slowly, throughout nearly the entire phreatic zone, with local flow velocities determined by both the magnitude of the hydraulic gradient and the size of the available openings. Because both of these velocity-controlling variables tend to decrease with depth, most groundwater flow (and hence, solution) takes place along paths that are generally near and parallel to the top of the phreatic zone.

Because the top of the phreatic zone is discontinuous in most karst regions, and because water within many solutional openings tends to move independently of water in nearby openings, the terms "water table" and "piezometric surface" are technically inappropriate in describing the boundary between the vadose and phreatic zones in limestone. The terms are useful, however, in general discussions that do not refer to specific locations or involve quantitative application. In this paper, to avoid misinterpretation, the movement of water along each solutional opening will be considered to be relatively independent, and the term *piezometric limit* will be used to define the point within a given flow path below which the flow direction is influenced by hydrostatic pressure. In some cases where flow is confined to a planar structure, the piezometric limit can be identified as a point where the major flow path changes from a dip-oriented to a strike-oriented trend. This point is determined both by the discharge rate and by the size and geometry of the openings and therefore may vary considerably not only between different openings, and at different positions within the same opening, but also as a function of time.

Floodwater flow is a term that can be applied to sudden increases in groundwater discharge in a cavernous terrane caused by intense rainfall or snowmelt. Analogous to flooding in a surface stream, and usually coincident with it, subsurface floodwater flow is most prominent in caves that receive direct runoff from sinking streams.

Contemporary Hydrology

The discharge of the sinking stream at Onesquethaw Cave varies between approximately 0.1 and 50 ft^3/second, with fluctuations that are extremely sensitive to local precipitation. The stream is the direct descendent of a surface tributary to Onesquethaw Creek that was originally perched on the relatively impermeable Wisconsin glacial till that mantles the limestone bench. Initial underground diversion of the stream took place at the present cave entrance, but later diversion through a swallow hole approximately 1000 ft upstream from the entrance has left much of the cave inactive, except as a route for periodic floodwaters (Fig. 4) and for the small amount of residual drainage from the abandoned valley downstream from the present swallow hole. Today the sinking stream emerges into Onesquethaw Cave along the fault zone (see plate) and flows through only 60 ft of explorable passages before disappearing into a narrow, water-filled connection with Jordan Cave. The frequent and severe flooding that characterizes Onesquethaw Cave is caused by the relative hydraulic inefficiency of this connection and of several narrow passages upstream from it. The main stream reappears in Jordan Cave and flows the length of the main passage at depths as great as 6 ft, ultimately resurging at the low, arched cave mouth (Fig. 5) and cascading over the escarpment of Schoharie Sandstone into Onesquethaw Creek.

Because so much of the flow in the system enters directly as a sinking stream, rather than infiltrating through the overlying soil and limestone, the groundwater is able to exert its maximum solutional capacity toward enlarging the cave instead of dissipating its cave-forming potential through surface degradation, a situation enhanced by the fact that soluble rocks are not exposed in the bed of the surface stream feeding the cave.

Developmental History of the Cave

At the end of the most recent glaciation (approximately 13,000 years BP), drainage was re-established on the structural bench of Onondaga Limestone as surface streams that were perched on deposits of glacial till. Where the till was thin or absent, water filtering from the stream beds passed downward in varying amounts along favorable bedding-plane partings and fractures, initiating the development of many of the caves in this area. Some solutional enlargement may have taken place before or during the latest glacial advance, although the known caves in the Onondaga bench are too well adjusted to the present drainage patterns to have undergone their major growth earlier than post-glacial times.

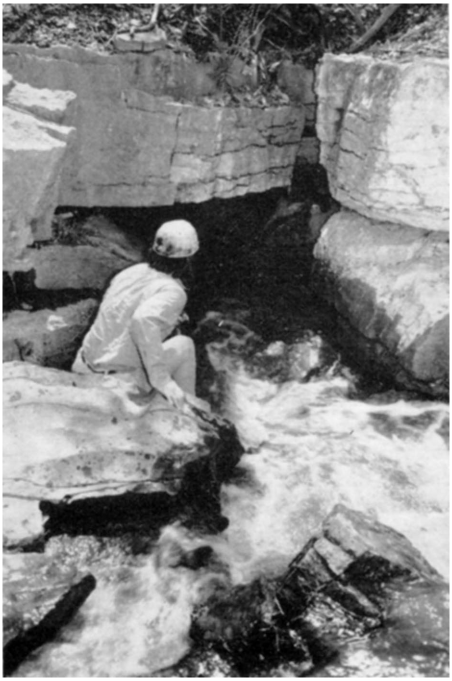

Figure 4. Entrance to Onesquethaw Cave during typical flood conditions (May 15, 1971). Although the entrance is ordinarily dry, it receives overflow from a sinking stream during periods of intense or prolonged rainfall or snowmelt.

Four major stages of development are suggested by the pattern of passages in Onesquethaw Cave (see Fig. 3). The limits of each stage are rather ill-defined because of the tendency for the cave to undergo periodic enlargement by floodwaters throughout its history. Nevertheless, as a useful frame of reference for the following

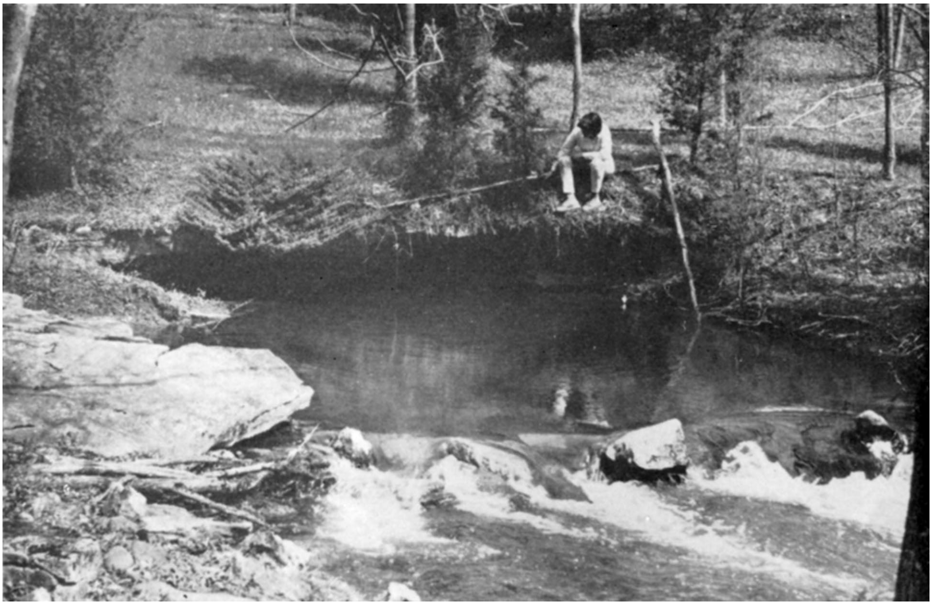

Figure 5. Resurgence of the Onesquethaw system at Jordan Cave during a period of moderately high discharge (approximately 30 ft^3/second). Water depth at this time was roughly 2 ft. The passage is locally enlarged along a prominent bedding plane as a tubular conduit with a bedrock floor.

sections, these stages are briefly outlined below:

Stage 1: Enlargement of a favorable bedding-plane parting, exposed in the bed of the surface stream that now feeds the cave, by subsurface diversion of progressively greater amounts of the available stream flow, leading to ultimate capture of the entire stream. Remnants from this stage to be found in the cave today are all confined to the single bedding plane that forms the ceilings of the entrance passage and nearby upper levels (see Fig. 6). Solutional widening of the bedding-plane parting was generally less than one foot. Capture of the surface stream appears to have taken place in two stages, forming in sequence the two parallel passages at the northwestern end of the cave (represented by cross sections D-E and A-B on the cave map). The outlet for this initial passage system is unknown; it terminates in breakdown and apparently does not re-enter the known parts of the cave.

Stage 2: Diversion of the subsurface flow to a complex lower route along the thrust fault and through the chert zone (cross sections C,F,H, etc., on cave map). Most of the main passages of the system were developed along this new flow path, including Jordan Cave, which acted as the outlet.

Stage 3: Downcutting by free-surface stream action as the passages enlarged enough to conduct all available groundwater flow. Some minor diversions to lower-level routes took place during this stage.

Stage 4: Subsurface diversion of the main stream through a swallow hole roughly 1000 ft upstream from the cave entrance, abandoning the entrance sections of the cave except during periods of flood. This new route, still active today, enters the cave along the fault in the Spider Room

Figure 6. Top of the 11-ft-deep entrance canyon, showing the enlarged bedding-plane parting along which the initial cave development took place. Vegetal matter lodged near the ceiling indicates periodic flooding of the entire cave.

and follows the pattern established during stage 3 through the remainder of the cave.

Floodwater enlargement of the cave has taken place mainly during the last two stages of cave development as the passages grew large enough to admit most or all of the peak flow in the main stream. Irregular enlargement of existing passages has taken place, in addition to the creation of floodwater diversion routes around passages whose enlargement was retarded by chert beds.

The cave has not undergone a distinct and widespread episode of filling by clastic sediments. The few existing bodies of sediment are the result of local (and generally temporary) decreases in load capacity of the stream, and are not remnants of formerly extensive deposits that once filled the cave.

Deposition of speleothems has been scant. Not only is vertical infiltration into the cave restricted almost entirely to the fault zone and to major joints, but the active flooding and dynamic aspect of the groundwater flow apparently create an environment that is not favorable to the precipitation of secondary minerals. Minor patches of flowstone and rimstone sparsely scattered throughout the cave commonly show evidence of partial re-solution.

INFLUENCE OF GEOLOGIC STRUCTURE AND STRATIGRAPHY ON CAVE DEVELOPMENT

The character and trend of Onesquethaw Cave have been determined by a complex interrelationship between flow dynamics and geologic setting. Although it is difficult to treat a single aspect of this interrelationship without drawing in all others, the treatment of geologic structure and stratigraphy in this section serves not only as a first step in understanding the peculiar morphology of the cave, but also as an orderly method of describing the cave in detail.

Four geologic features have exerted significant control over passage development: (1) the low-angle dip at the northwestern end of the system, (2) the reverse fault and joints associated with the compressive forces that formed the fault, (3) the anticline that intersects the eastern end of the system, and (4) the irregular and discontinuous zones of chert beds. The location of each of these features, as observed from exposures in the cave, is shown in Fig. 3.

Influence of Low-Angle Dip

The initial passages of the cave system that developed during stage 1 are located in the area of low dip (approximately 2.5 degrees to the southeast). The two passages in this area—which may be recognized on the map of the cave by the cross sections labelled A,B,D, and E—are both roofed by a single bedding plane that intersects the land surface at the cave entrance. The passages are oriented almost directly down the dip, with only a minor amount of sinuosity and deviation from the downdip direction, except for a conspicuous shift to strike orientation 80 ft beyond cross section B. This change in trend seems to have been determined by the piezometric limit, rather than by geologic structure, as the passages follow the same bedding plane faithfully throughout their explored length. Downcutting by free-surface streams has followed the original passage pattern, creating canyons 2 to 3 ft wide and of varied depth (Fig. 6) which today discharge their water into the fault-oriented passage.

Influence of Fault and Joints

In spite of the strongly jointed aspect of nearby surface exposures of Onondaga Limestone, only about 20% of the passage development has taken place along joints or along the reverse fault in Onesquethaw Cave. Although the fault extends through the very heart of the cavernous zone, solutional enlargement along the fault is discontinuous, represented mainly by high fissures at points where the fault is intersected by meandering bedding-plane passages (Fig. 7). The fault and several major joints have played an important role in the development of the cave, however, by providing paths for groundwater to pass from one stratigraphic horizon to another. For instance, each of the five points of intersection between the main passage and the fault zone is represented by a fissure enlarged both vertically and laterally along the fault, with the entering passage developed within entirely different beds from those of the exiting passage.

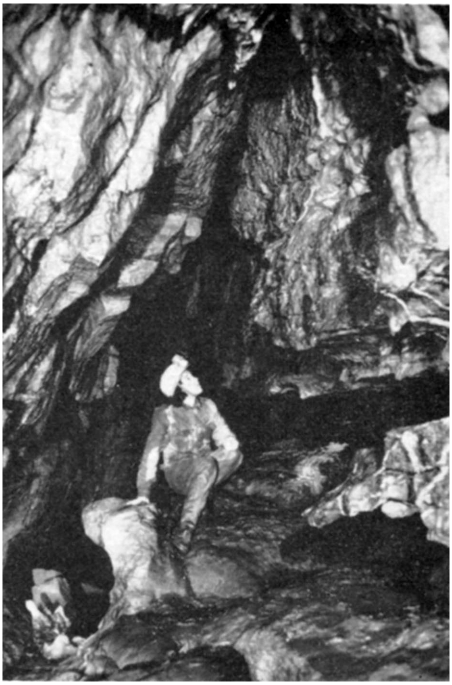

Figure 7. The Spider Room, located along the fault zone near the point where the sinking stream resurges into the cave. The narrow fissure in the ceiling rises to heights of 10 to 15 ft above the roof of the main passage, which enters from the right. (The minor offset along the fault, not apparent here, is shown in Fig. 9.)

Although their effect on the passage pattern is minor, numerous joints exposed in the cave are expressed as solutional fissures transverse to the main passage trend, as best shown in the canyon series in the area of gentle dip. Also noteworthy are the conspicuous angular passage pattern and fissure-like cross sections (as in cross section Q) where the cave crosses the axis of the anticline and utilizes several intersecting joint sets as the main path for ground-water movement. A slight tendency for joint control is also found along the axis of the broad, asymmetrical syncline (upstream from cross section J) where the gentle dip in the northwestern end of the cave reverses to form the west limb of the anticline.

Influence of Anticline

Nearly all passages that have developed along the anticline are strongly strike oriented (cross sections P,R,S,T). This orientation is apparently the result of solution along the top of the phreatic zone at its intersection with the steeply dipping bedding planes along the limbs of the fold. Topographically the most favorable outlet for the subsurface drainage is located on the opposite side of the anticline from the entrance sink. As a result, the main path of flow established a route that cuts across the axis of the anticline approximately where the fold axis intersects the fault zone midway through the cave, a structural setting that apparently offered the most efficient path of flow between the intake point and the outlet.

Thick calcite veins along certain bedding planes suggest a large amount of differential movement between adjacent beds during deformation of the region. Such movement may have contributed to the predominant bedding-plane orientation of passages along the anticline by weakening the bonds between beds and causing actual separation along bedding planes. The calcite veins themselves have had virtually no influence on passage patterns.

The prominence of bedding planes in controlling the development of this part of the cave has resulted in elliptical passage cross sections elongated parallel to the dipping beds (Fig. 8). Because of a combi-

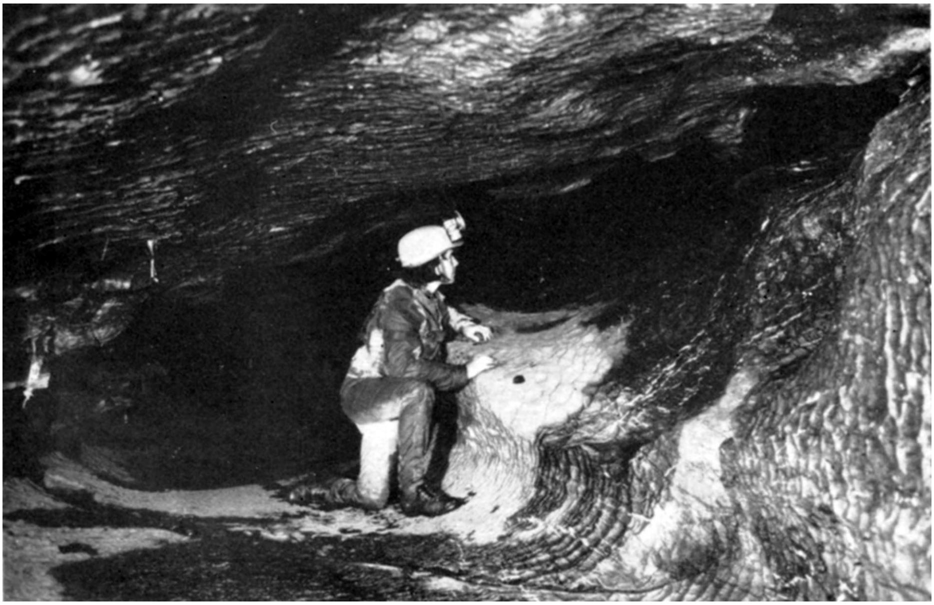

Figure 8. Main passage beyond the Spider Room, developed along the strike on the flank of an anticline. Note the gash veins of calcite and prominent scalloping in the walls. Along the same bedding plane, the present low-flow path for the main stream is located slightly down the dip from this passage, with floodwater diversion channels extending in the up-dip direction.

nation of the slight plunge of the anticline to the southwest and the gentle passage gradient to the northeast, the main passage of the system migrates away from the axis of the anticline in the downstream direction.

Influence of Chert Zones

Strange as it may seem, the strong bedding-plane control of groundwater and the concordance of cave passages to the geologic structure are largely absent where the limestone contains interbedded chert. Instead of being confined to the limestone layers that are sandwiched between the rather continuous and insoluble chert beds, the flow is strongly discordant to the bedding and migrates in irregular patterns both upward and downward from one bed to another (see profile on cave map). Most passages of this type are roughly oblong in cross section, because they are locally widened along the limestone beds but retarded in vertical development by the chert beds (as in cross sections F and K). Solutional widening of passages along bedding-plane partings, so characteristic of passages in the chert-free zones, is generally absent, except along the uppermost limestone-chert contact (Fig. 9). The chert appears to form a cement between the limestone beds so that the entire sequence of alternating limestone and chert acts as a single competent structural unit with few, if any, partings. This relationship can be observed in the middle sections of Onesquethaw Cave, where several thick but discontinuous chert beds grade laterally into prominent, solutionally enlarged partings in the limestone.

Much of the coarse-grained sediment in the cave is derived from the chert beds, which protrude from the cave walls in considerable relief, locally forming minor natural bridges across passages. The chert tends to break off in angular blocks and weather by stream abrasion to rounded pebbles that clog many lower-level passages in the cave.

INFLUENCE OF HYDROLOGY ON PASSAGE PATTERN

Although, as shown in the preceding section, the local character of passages in Onesquethaw Cave is strongly influenced by geologic structure and stratigraphy, the overall passage pattern is determined mainly by an intricate hydrologic setting that has involved several different flow regimes both in the past and at present. Highly variable recharge to the system through the sinking stream, in combination with the diverse geologic setting, has produced a dynamic and complex history of cave development. This representation of floodwater cavern development is in direct opposition to that of many karst researchers who tend to consider a cave fed by a sinking stream as invariably the simplest form of groundwater flow through limestone.

Vadose Cave Development

Although perennial, the surface stream responsible for the origin of Onesquethaw Cave was perched some 30 ft above the phreatic zone during the first stage of its development. The perched condition of this stream is evident from the fact that except for minor deviations the passages below its surface bed are oriented almost directly down the dip of the prominent bedding-plane parting that afforded the path for subsurface piracy. This relationship indicates a hydraulic potential resulting from gravitational force only, with little or no change in pressure along the flow paths.

This flow has resulted in passages of considerably different pattern and character from other parts of the cave system. The entrance passage and its adjacent upper levels are oriented perpendicular to the major trend of the cave, as well as to the topographic gradient and overall trend of groundwater flow in the Onondaga bench. Both passages have ceiling gradients of 2.5 degrees, coinciding with the local dip, which are roughly four times greater than the average gradients of other passages in the cave. They are gently curvilinear in horizontal pattern, apparently influenced by irregularities along the bedding-plane part-

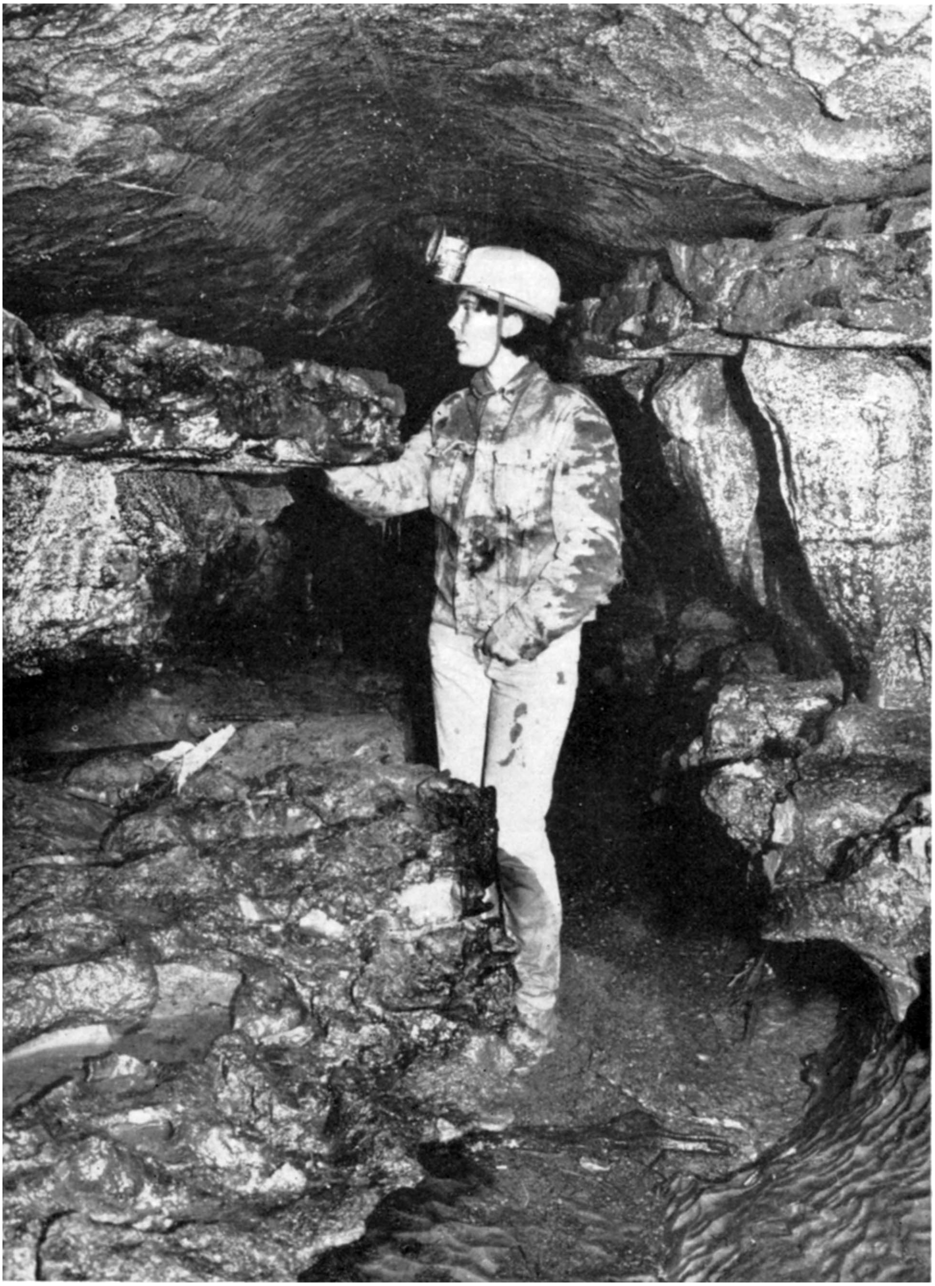

Figure 9. Fault-controlled passage in the zone of prominent chert beds, located near cross section C on the cave map. Note the fault trace in the ceiling and floor and the offset of the chert beds.

ing, and exhibit little joint control, even though numerous transverse joints have been enlarged outward from the passages. Remnants of anastomoses along the enlarged ceiling bedding plane suggest that the initial solution was at least partly performed by water that filled the entire opening, although any pressure differences that resulted must have been of short enough duration to have had no effect on the passage trends.

The perched aspect of this flow is further indicated by the fact that canyon development by free-surface streams was initiated in the dip-oriented sections before the original channels had enlarged more than a few inches, while the strike-oriented segment continued to enlarge as an elliptical tube to vertical dimensions as great as 4 ft. The vadose canyons, still deepening today by overflow and residual infiltration from the sinking stream, have intersected a second major bedding plane 4 ft below the ceiling bedding plane, which has enlarged laterally several feet in each direction, revealing the prominence of bedding-plane partings in this locally chert-free section of limestone (cross section A).

Graded Passages Formed by Phreatic Flow

Several passages in Onesquethaw Cave have relatively graded profiles that are determined not by structure but by the piezometric limit within joints or bedding-plane partings. (A graded profile is considered here as one having a slope that is relatively uniform and that is consistent in the downstream direction.) The majority of flow and cave enlargement in these passages has apparently been confined to the top of the phreatic zone by the decreasing openness of partings and joints with depth, by the tendency toward decreasing hydraulic gradients along deeper flow paths, and by deposition of clastic sediment along deeper paths. Even though differences in pressure have been relatively minor or entirely absent, and even though the flow may have had a free surface, the flow paths have been determined by both gravitational and pressure gradients and therefore represent "shallow phreatic," rather than vadose, cave development. Where initial recharge from the sinking stream reached the piezometric limit within the controlling bedding-plane parting, it changed course from a downdip trend to a trend nearly parallel to the strike (cross section G), in the direction of the outlet in the nearby surface valley. Other passages that conform to this "shallow phreatic" pattern include the main passage between the Spider Room and the terminal sump in Onesquethaw Cave and most of Jordan Cave. In the former, a drop in the piezometric limit (in response to a lowering of the outlet or an increase in hydraulic efficiency) has resulted in migration of the active level to a course parallel to the original but located down the dip along the same favorable bedding plane (see easternmost two passages in cross section T). Graded, phreatic passages in the Onesquethaw system have gradients of less than half a degree.

Ungraded Passages Formed by Phreatic Flow

Several passages in the cave system show evidence of having formed within the phreatic zone, entirely below the piezometric limit. Passages of this type generally "meander" vertically as well as horizontally and therefore have ungraded profiles that show little relationship to the erosional base level or to local piezometric limit. The main passage of Onesquethaw Cave between the entrance canyon and the Spider Room and the flooded connection with Jordan Cave have ungraded profiles undoubtedly of phreatic origin, for they contain highly irregular bedrock floors that in several places have elevations higher than ceiling levels in upstream reaches (see profile on cave map). Cave development is currently taking place below the spring level in the Onesquethaw-Jordan connection and in the downstream parts of the present sinking-stream course that discharges into the Spider Room. The spring at Jordan Cave shows no evidence of having once occupied a lower level that would have allowed these presently active passages to be partially or completely air filled in the past because the passage that feeds the spring is floored with bedrock and abandoned lower-level spring alcoves or seeps have not been found.

In contrast to the uninterrupted bedding-plane partings along which the graded passages have formed, the ungraded phreatic passages of the cave system occur within geologic settings of considerable diversity. Between the entrance passage and the Spider Room, the main passage of Onesquethaw Cave cuts discordantly through the chert-rich zone and across the axis of the anticline, intersecting the normal fault in several places; the flooded passage connecting Onesquethaw with Jordan Cave passes discordantly through a strongly jointed, chert-rich zone in the limestone; and the low-flow resurgence of the sinking stream into the Spider Room is located along the fault in a 10-ft-deep pool. In none of these ungraded passages is there a single structural opening prominent or continuous enough to provide an uninterrupted flow path along the top of the phreatic zone.

Perhaps the most unusual section of ungraded passage in the cave is located at the end of the Barnyard, where a low, wide passage enters a joint-controlled fissure cutting transversely across the passage, and exits from the fissure by doubling back under itself in a 180-degree bend (cross section L).

The ungraded channels presently occupied by the main stream are located at levels below that of the spring and are perennially flooded. Those that are now above the spring level, such as the main passage of Onesquethaw Cave in the vicinity of the Barnyard and Otter Slide, are active only during periods of high flow because of diversion of the main stream to a new route. Except for times when the sinking stream overflows into the Onesquethaw entrance, the minor amount of flow in the passages upstream from the Spider Room follows narrow, flooded joints and partings below the level of the abandoned main passage.

Passages Formed by Periodic Floodwaters

Except for a few minor tributaries, the basic pattern of the Onesquethaw Cave system is that of a single stream course with diversion routes to lower levels. Superimposed upon this essentially linear pattern, however, are numerous interconnecting passages apparently developed by the periodic floodwaters that invade the cave.

In areas of diverse lithology, differential enlargement of the main flow routes tends to produce passages that vary a great deal in hydraulic efficiency along their length. During periods of high flow, water is often impounded behind passage constrictions under considerable pressure. Local hydraulic gradients in the suronding limestone (much greater than those normally found under phreatic conditions) become high enough to develop numerous blind pockets and diversion passages, which are quickly enlarged by the turbulent, solutionally aggressive floodwater.

Constrictions of this type in Onesquethaw Cave are located in the chert-rich zones where solutional enlargement of passages is retarded by the exposure of varying amounts of insoluble chert. For example, many of the passages contain crawlway segments developed in limestone beds no more than one foot thick, bounded above and below by continuous chert beds (Fig. 10). Floodwater passages are found either upstream from or bypassing such constrictions in the main passage of the cave. In areas of chert-free limestone, however, such as the vadose canyons in Onesquethaw Cave and the downstream sections of Jordan Cave, passage enlargement is relatively uniform, so that there is little or no tendency toward the development of floodwater diversion routes.

The passages of floodwater origin in the Onesquethaw system, shown in Fig. 3, form an anastomosing pattern of diversion or overflow routes for peak flow, the most prominent of which include the maze of crawlways above the main passage beyond the Spider Room (upper levels of cross sections R, S, and T) and the overflow passages parallel to the Barnyard (cross sec-

Figure 10. Constriction in the main passage of Onesquethaw Cave, locally bounded above and below by insoluble chert (lower part of cross section L on cave map). The water depth is approximately 6 inches.

tion K). Most of these passages are ungraded, tubular crawlways forming closed loops with the main passage, with an apparent tendency to form at levels slightly higher than the original inefficient route, commonly along the same geologic horizon. Prominent solution scallops in their walls indicate the presence of turbulent flow at minimum velocities of 3 to 8 ft/second.

Floodwater flow appears to have been directly responsible for the most salient feature of Onesquethaw Cave, its curious and confusing "braided" pattern. A true understanding of the hydrology and cave-forming processes within this and similar karst areas depends upon an unbiased knowledge of floodwater processes and upon the ability to recognize passages of purely floodwater origin. It is to these problems that the following section is devoted.

A Discussion of Floodwater Processes

Of primary concern in an understanding of Onesquethaw Cave is verification of the hypothesis that floodwaters are capable of initiating the development of cave passages above the low-flow piezometric limit. This task is difficult, in view of the fact that the most prominent features of the supposed floodwater passages are precisely those that have been used for decades to support a *phreatic* cave origin. These features include (1) maze pattern, (2) branching in downstream direction, (3) ungraded profiles, (4)continuous rock spans across passages, and (5) wall and ceiling pockets, generally expressed as joints enlarged vertically or laterally from the passages. The confusion with true phreatic development is understandable, as floodwater flow can be considered a return of "phreatic" conditions to the lower parts of the vadose zone.

Because true phreatic conditions require saturation of rock with ground water on a perennial basis, most phreatic flow during the year is represented by the comparatively low base flow between storms. Floodwater flow, in contrast, often involves velocities, hydraulic gradients, turbulence, and solutional aggressiveness hundreds of times greater than those under average phreatic conditions and occurs in its most formidable aspects only in caves fed by sinking streams. Whether the bulk of floodwater flow passes through abandoned upper-level passages, through closed conduits in the phreatic zone, or through overflow routes of its own creation, such a dynamic medium is likely to leave its own distinctive features superimposed upon, or completely obliterating, any cave features that existed previously. As a consequence, to distinguish passages of purely floodwater origin from those of different origin that have been modified by subsequent floodwater activity is difficult.

To prove that the maze passages and closed loops in Onesquethaw Cave were developed above the normal piezometric limit by high-gradient floodwaters, attention is centered on the anastomosing crawlway system parallel to the main passage beyond the Spider Room. Developed along a single dipping bedding plane on the southeastern limb of the anticline, these passages meander slightly up and down the dip, ascending to elevations as great as 20 ft above the active stream level and finally descending to the level of the stream at the northeastern end of the cave (see profile on cave map). With a base flow of 0-1 ft^3/second through the cave, these passages could not have been formed at or below the piezometric limit: between these passages and the spring at Jordan Cave the gradient is much too high to have allowed such a meager discharge to maintain flooded conditions within them. To be specific, at this discharge a hydraulic head of 15 to 20 ft with respect to the spring could exist only if the average diameter of Jordon Cave were less than half a foot.[*] Further growth in the passage size would have caused a rapid drop in water level in Onesquethaw Cave. As can be observed today, during all but flood conditions, the stream at the end of Onesquethaw Cave disappears readily into a tiny, sediment-choked channel less than 1 ft in diameter without ponding upstream. With a present average diameter of at least 3 ft in the flooded passage between the two caves (determined by diving) a flow of more than 30 ft^3/second is required to flood completely the rear portions of Onesquethaw Cave.

If the Jordan Cave spring had occupied a higher elevation during the development of the maze passages, however, these passages could have undergone most of their development under true phreatic conditions, rather than under the floodwater conditions suggested above. In opposition to this idea, (1) the main Jordan Cave passage is as large as any in the entire system, suggesting that it has been the main outlet during most or all of the development of Onesquethaw Cave, and (2) for a distance of several hundred feet upstream from the final Jordan spring there is only 2 to 10 ft of bedrock overlying the cave passage, a fact that argues against the possibility that Jordan Cave formerly discharged upward through a Vauclusian spring, thus allowing the upstream maze passages to remain flooded. These relationships are shown in the profile on the main cave map and in Fig. 5.

A former groundwater discharge greater than that of today cannot be invoked as a means for maintaining phreatic conditions within the maze passages during their growth. The post-glacial origin of the cave, inferred from the perched condition of the cave-forming sinking stream on Wisconsin till, suggests that the climate and rainfall have not changed radically since the initial

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[*] This value is obtained from the Darcy-Weisbach equation for flow through a closed conduit:

$$Q = \left(\frac{8\,R\,g}{f} \cdot \frac{\Delta h}{L}\right)^{1/2} A \ ,$$

where Q = discharge, R = hydraulic radius (cross-sectional area/wetted perimeter), g = gravitational field strength, A = cross-sectional area of conduit, $\frac{\Delta h}{L}$ = hydraulic gradient (15 ft/1000 ft in this example), and f = friction factor depending on roughness and size of channel and on turbulence of flow (approximately 0.05 for limestone channels under highly turbulent flow conditions, where the deviation from a circular cross section is not great).

development of the cave and that the average discharge through the system has remained relatively constant.

Because most of the floodwater features of Onesquethaw Cave are apparently caused indirectly by constrictions in the active passages, an examination of the hydraulic characteristics of constrictions of this type is instructive. As water flows through passages of varying cross-sectional area, the velocity within constrictions increases by the same factor that the cross-sectional area decreases. A great amount of energy may be lost in such an area as water is forced to converge into the narrow segment of passage, pass through it, and diverge at the other end (see Appendix I). An increase in head is required at the upstream end of the constriction to maintain constant flow within the passage; the result is ponding at this point, with an increase in water depth and pressure. During peak flows in Onesquethaw Cave, in which abrupt cross-sectional area changes of five to ten times are common, pressure differences across local constrictions are calculated to be as great as 1500 lb/ft^2.

The linear dependence of velocity upon the groundwater discharge rate causes the hydraulic gradient through the constriction to increase with the *square of the discharge.* The importance of peak flow, or floodwater flow, in creating diversion passages throughout the surrounding limestone is apparent: as the discharge increases in response to a storm, water is impounded behind the constriction with a steep hydraulic gradient both across the constriction as well as into the previously unsaturated limestone upstream from the constriction. Diversion passages, in addition to blind tubes and pockets, enlarge at a comparatively rapid rate due to the turbulent and solutionally aggressive nature of the floodwater. Great variation in passage cross section may be a by-product of this process in the areas of most severe flooding, where passages are enlarged upward and laterally along joints and partings.

Constrictions in an active cave passage normally require that one or more of the following conditions be met: (1) exposure of relatively insoluble material in the cave walls, (2) clogging of the channel with stream-borne clastic debris, (3) collapse of the cave passage, or (4) blockage of the spring outlet by alluvial or glacial deposition. Factors (1) and (2) have been most prominent in causing passage constrictions and their associated floodwater phenomena in Onesquethaw Cave. Collapse near the terminus of Jordan Cave may have acted as a temporary barrier to flow through the system, but any effect upon the hydraulic character of the cave has apparently been minor.

The increase in velocity through a passage constriction may cause a higher solution rate along the soluble walls of the constriction than in the areas of larger cross section. The existence of numerous prominent and abrupt reductions in passage size within Onesquethaw Cave, however, shows that the effect of this differential solution rate is not great enough to eliminate the disparity in cross-sectional area. If the solution rate is assumed to be proportional to no more than the first power of the flow velocity*, it can be shown (Appendix II) that any part of a passage sandwiched between insoluble beds theoretically will enlarge more slowly in cross-sectional area than other parts of the same passage that are either bounded only on one side or entirely unbounded by insoluble material,

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* Crude experiments conducted by Kaye (1957) suggest a linear relationship between the solution rate of calcite and the velocity of solvent hydrochloric acid. Wigley (1971) has verified this observation analytically, showing that a tube with soluble walls will enlarge at a rate almost directly proportional to the flow velocity of turbulent solvent within the tube, with a relaxation length that is nearly independent of the flow velocity but directly proportional to the tube radius (assuming that the solution rate is limited only by the rate of mass transfer of solute ions away from the tube walls). For the solution of limestone by carbonic acid, however, Curl (1968) has demonstrated that the solution rate may be retarded considerably by the slow hydration rate of carbon dioxide in water, which limits the availability of hydrogen ions in the solvent and therefore may suppress the tendency for greater solution rates under increasing velocities.

in spite of the fact that the former segment maintains higher flow velocities. As a consequence, the disparity of passage size increases with time because of the slower rate of enlargement in the chert-bound passages.

The tendency for development of floodwater diversion passages has evidently increased with time as Onesquethaw Cave enlarged. The narrow solution tubes with relatively uniform cross-sectional areas that must have characterized the initial stages of the system were capable of transmitting only a limited amount of water, forcing excess discharge to follow the original surface channel. Hydraulic gradients were rather uniform because of the general lack of transmissivity variations within the passages. As the cave has enlarged, it has increased its hydraulic efficiency to the point where it can transmit the entire available stream flow but with increasing variation in cross-sectional area because of the heterogeneous geologic setting. The hydraulic gradient has become highly irregular, especially under flood conditions when relatively little head loss occurs in the large passages compared with that in the constrictions. Development of diversion passages has occurred in the areas of locally steep hydraulic gradients, mainly in the vicinity of the chert-bound crawlways.

Because of the high velocities of groundwater flow that occur during periods of peak discharge, the processes of erosion and deposition, as well as solution, are prominent in caves that are fed by sinking streams, Not only do passages in Onesquethaw Cave change visibly in shape from year to year, but new passages are periodically made accessible by erosion of clastic fill, while formerly accessible passages have been entirely obscured by detrital material deposited by floodwaters. A broad limestone ledge 75 ft downstream from the Otter Slide was reduced 3 to 6 inches in height by solution and corrasion within the period 1961-1967, as measured from several distinctive coral fossils in the adjacent walls. Over the same period, several crawlways accessible from the bottom of the fissure beyond the first crawlway in the cave (cross section G) were entirely filled with clastic debris. During a single storm in 1970, more than 12 ft of sediment was deposited in this same fissure, and its access crawl (cross section F) was half filled with the same material, which consisted of sand and platey shale particles largely derived from the Hamilton beds overlying the Onondaga. Some results of this storm are shown in Fig. 11.

The cave map does not portray changes in bedrock features and fill levels that have occurred since August, 1969. Not only would revisions of the map be quickly outdated, but the existing map may be useful for

Figure 11. Sediment and vegetal debris that was deposited in this joint-controlled fissure to depths as great as 12 ft during a single flood in 1970. This location is shown in the lower part of cross section G, although the sediment accumulation is not indicated on the map.

determining the rate and magnitude of changes that take place within the cave. Among the visible changes that have occurred since completion of the survey, the lower passage in cross section G has nearly been filled with sediment, the crawlway in cross section F has gained a prominent gravel bank along its north wall, and a natural bridge of chert at the entrance to the same passage has been removed by erosion.

SUMMARY

The following statements regarding floodwater cave development have been concluded from this study and are supported by observation of floodwater caves in other karst areas:

1. In a region of varied geologic structure or lithology, the hydrologic setting of the underground components of a sinking stream system can be extremely complex, with active phreatic, vadose, and floodwater cave development occurring simultaneously.

2. In areas of diverse geology, the most characteristic pattern for a cave fed by a sinking stream is that of a single stream course with a superimposed network of diversion or overflow routes. A single graded stream passage of relatively constant cross section is more characteristic in areas of uniform lithology and little structural deformation.

3. Most solution features commonly used as criteria for phreatic cave development are best exhibited in passages of floodwater origin or in those that have been extensively modified by floodwaters; therefore, these criteria cannot be used as conclusive evidence for a true phreatic origin, because many floodwater passages develop above the low-flow piezometric limit.

4. Maximum development of floodwater features is dependent upon extreme variations both in discharge and in cross-sectional area within the active stream passage.

5. In areas of diverse lithology, floodwater processes in an active cave appear to increase with time, because of increasing disparity in cross-sectional area between constrictions and passages whose growth is not impeded by insoluble beds.

In addition, the following conclusions relate specifically to Onesquethaw Cave and to other caves in the Onondaga Limestone having a similar hydrologic setting:

1. Developmental processes in Onesquethaw Cave appear to be no less active today than they have been in the past.

2. Despite its direct relationship to open-channel flow on the surface, more than half of the present path of the main underground stream in the Onesquethaw system is closed-conduit, phreatic flow.

3. Vadose passages have steep gradients controlled mainly by the dip of the strata, whereas phreatic and floodwater passages are generally ungraded and strike oriented, with overall gradients of less than half a degree.

4. Although many passages are highly concordant to the geologic structure, there is a strong discordance between passages and structure in areas of prominent chert beds, because the "cementing" effect of chert upon adjacent limestone beds in the Onondaga Limestone reduces the availability of prominent bedding-plane partings.

In spite of its apparent simplicity, cave development by subsurface stream diversion may involve interrelationships between flow dynamics and the geologic setting that are among the most complex of all karst processes.

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Manuscript received by the editor, January, 1972

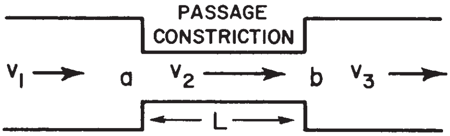
APPENDIX I

Head Loss at a Passage Constriction

At any point in a flow system, the total hydraulic head (h), or energy per unit weight of fluid, can be expressed as

$$h = Z + \frac{P}{\gamma} + \frac{\alpha v^2}{2 g}$$

where Z = elevation with respect to an arbitrary datum (e.g., sea level), P = fluid pressure, γ = specific weight of fluid, v = mean fluid velocity, g = gravitational field strength, and α is a factor that varies from 2.0 for laminar flow to slightly more than 1.0 for highly turbulent flow. In a cave system, the hydraulic head (with respect to the outlet point) forces water to move against the resistive effects of wall friction and fluid viscosity. Head is therefore consumed in the direction of flow at varying rates depending upon the hydraulic efficiency in each segment of passage. Constrictions in the passage consume more energy per unit length of flow than segments of larger cross-sectional area, creating a relatively steep hydraulic gradient in the vicinity of each constriction.



In a water-filled passage of varied cross-sectional area, shown in profile in the generalized diagram above, the head lost by the water as it passes through the constriction is equal to the sum of the following terms:

1. Head loss at entrance to constriction (point *a*) = $K_a \frac{v_2^{\,2}}{2 g}$, where v_2 is the average velocity of flow through the constriction, and K_a is a factor that varies up to roughly 0.5 according to the geometry of the constriction.
2. Head loss at passage enlargement (point *b*) = $K_b \frac{(v_2 - v_3)^2}{2 g}$, where K_b is a factor that varies up to 1.0 according to the geometry of the enlargement.

3. Head loss within the constriction (between points *a* and *b*) in excess of that lost over a comparable length of the unconstricted passage =

$$\frac{L\,f}{8\,g}\left(\frac{v_2^2}{R_2}-\frac{v_1^2}{R_1}\right),$$

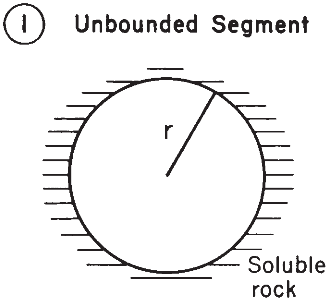
where L is the length of the constriction, f is a friction factor (roughly 0.05 for circular conduits in limestone), and R_1 and R_2 are the hydraulic radii in the constricted and unconstricted segments respectively.

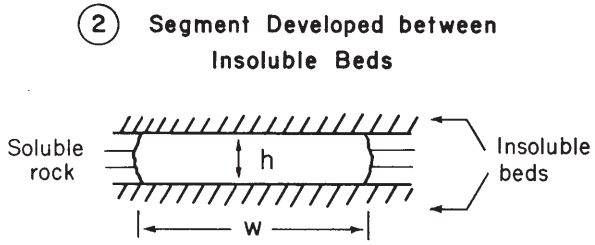
Each of these terms is dependent upon the square of the velocity and therefore, for any given point in a flow system, increases with the square of the discharge. As the subsurface discharge becomes greater during flood periods, there is a geometric rise in the head loss at passage constrictions, manifest mainly as a pressure difference across the constriction. Further discussion of head loss under turbulent flow can be found in any elementary handbook of hydraulics.

APPENDIX II

DIFFERENTIAL ENLARGEMENT OF PASSAGES IN LIMESTONE CONTAINING THIN INSOLUBLE BEDS

Given a cave passage with segments that are partially bounded by insoluble beds alternating with segments that are unbounded, as the result of stratigraphic lensing or change in geologic horizon:





Assuming that the solution rate varies linearly with the mean flow velocity (v), an expression for the difference in enlargement rates between the two passage segments shown above can be developed as follows:

Where A = cross-sectional area,

$$A_1 = \pi r^2 \quad ; \quad A_2 = wh$$
$$dA_1 = 2\pi r dr \quad ; \quad dA_2 = hdw$$

Dividing by dt,

$$\frac{dA_1}{dt} = 2\pi r\frac{dr}{dt} \quad ; \quad \frac{dA_2}{dt} = h\frac{dw}{dt} \qquad (a)$$

where $\frac{dA}{dt}$ is the rate of enlargement of passage area with time, and $\frac{dr}{dt}$ and $\frac{dw}{dt}$ are terms that represent the solution rate (i.e., rate of wall retreat) within segments (1) and (2) respectively. The discharge (Q) is constant within any length of conduit that does not gain or lose water through side passages:

$$Q = vA = \text{constant};$$
$$\text{therefore, } v_1 A_1 = v_2 A_2$$

and because the solution rate is assumed here to vary linearly with flow velocity,

$$A_1 \frac{dr}{dt} = A_2 \frac{dw}{dt}$$

$$\pi r^2 \frac{dr}{dt} = wh \frac{dw}{dt}$$

$$\text{therefore, } \frac{dr}{dt} = \frac{wh}{\pi r^2} \left(\frac{dw}{dt} \right) \qquad \text{(b)}$$

Combining equations (a) and (b),

$$\frac{dA_1}{dt} = (2\pi r) \frac{wh}{\pi r^2} \left(\frac{dw}{dt} \right) = \frac{2w}{r} \cdot \frac{dA_2}{dt} \quad ,$$

which shows that under assumptions previously stated the cross-sectional area in segment (1) will increase more rapidly than that of segment (2) whenever the width of segment (2) is more than twice the radius of segment (1), even though the solution rate is greater in segment (2). (The same relationship holds true where the larger segment is semi-circular in cross section and bounded along its diameter by an insoluble bed.) Early in their development, the two passage segments should enlarge at roughly the same rate until segment (2) becomes impeded in its growth by the insoluble beds. At this stage, r is already of lesser magnitude than $2w$, so that the increase in cross-sectional area from this time on is never as great in segment (2) as it is in segment (1). Consequently the disparity in passage size increases with time.

Preliminary Results on the Groundwater Geochemistry of the Sierra de El Abra Region, North Central Mexico

Discussion

John Fish [1] **and William Russell** [2]

Objections to Harmon's interpretation of the groundwater chemistry in the Sierra de El Abra (Bull. Natl. Speleol. Soc., 33(2):73-85, 1971) arise from several factors, most notably lack of attention to local geography, failure to consider the special chemical nature of many of the springs of the El Abra region, use of inadequate data to support his conclusions, and a crucial arithmetic mistake in the erosion rate.

Some of the geographic mistakes are more comic than substantive (such as labeling Cueva Chica, Cueva de Chica), but others, such as the sampling of only two of the "seven major springs" that drain the Sierra de El Abra and the failure to include such major resurgences as the Nacimiento del Río Tantoán and the Nacimiento del Río Choy on the location map or in the text, tend to give an erroneous impression of the area. Also it is not possible to tell from his discussion if he regards the Nacimiento del Río Frío as a Sierra del El Abra spring or if he regards it as being outside the area. Río Frío data should not be included with the El Abra data, as the source area for this spring (nacimiento) is a much higher mountain range to the north of the Sierra de El Abra, and springs in this range have different chemical characteristics from those in the El Abra. The idea that "cavern development has occurred throughout the range but is much more prevalent along the gently dipping western limb" results from a concentration of known caves along the western edge of the range, but this knowledge is due to the proximity of a major highway.

Harmon's research should have included a more thorough study of the El Abra springs, especially so because the sulfurous springs were obviously different. The springs may be divided into three types: (1) small springs from local El Abra limestone sources, with total hardness of about 230 ppm $CaCo_3$; (2) the two large springs, Nacimiento del Río Mante and Nacimiento del Río Choy, that mix El Abra water with deeply circulating, perhaps artesian, dolomitic and calcium sulfate waters derived from recharge areas far to the west; and (3) small thermal, sulfurous springs, such as at Hotel Taninul and at Los Banitos, south of Ciudad Valles. The origin of the sulfurous water is problematical; one possibility would be reduction of the sulfate species to various sulfur complexes when passing through hydrocarbon zones. Part of the water dis-

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charging from the thermal springs is derived by infiltration into the El Abra.

Another problem is the accuracy of some of the measurements. Ion balance calculations on some of the solutions for which the major ions—calcium, magnesium, bicarbonate, and sulfate—have been measured indicate that as many as half of the anions have not been identified. Data collected by Fish is in general agreement except that sulfate concentrations up to 500 ppm have been measured at the Choy and Mante springs under dry season conditions. These concentrations certainly cannot be ascribed to pollutants because most of the recharge area for these springs is uninhabited. Harmon does correctly point out the importance of the Ca/Mg ratios and the high carbon dioxide partial pressure. However, contrary to what he says, these facts do not give an order-of-magnitude increase in calcium concentration.

There are two major objections to Harmon's conclusions. The first is that the diagram (Fig. 6) that shows seasonal changes in degree of calcite saturation and calcium concentration in the cave and spring waters cannot be supported by the data. While seasonal fluctuations in saturation and calcium concentration are certainly possible, there is simply not sufficient data to draw his curves. The table below gives all the observations of spring water listed by Harmon, although the Nacimiento del Río Frío is not an El Abra spring:

	Date: 1/70		*Date: 5/70*	
Place	*Ca+ conc.*	*Log SC*	*Ca+ conc.*	*Log SC*
Nacimiento del Río Mante	300 ppm	+0.32	246 ppm	+0.30
Nacimiento del Río Santa Clara	133 ppm	+0.09		
Nacimiento del Río Frío	255 ppm	+0.64	144 ppm	+0.08

That two sample times is insufficient to define a curve is amply demonstrated by the fact that all the curves have been inverted; i. e., they show the opposite trend to that stated by Harmon. Furthermore, inspection of the data for cave sites which have been sampled twice does not yield any clear-cut trends. In any case, the major chemical changes have been found to occur with floodwaters pulsing the aquifer. Large storms or extended rainy periods greatly reduce the saturation and hardness values at the two large springs; a slow return to normal chemical conditions follows over a period of some weeks after the flood pulse has passed.

The second major objection is to Harmon's conclusion that the solution rate is "25 m^3 for an area of about 1,500 square kilometers." The actual rate of solution calculated from Harmon's data is 25,000 m^3. This error is especially serious because the 25 m^3 figure appears in the abstract. Harmon also implies that major cavern development has occurred only since the last continental glaciation, 10,000 years ago. He supports this idea by noting that use of the 25 m^3/year solution rate gives a volume of cave formed in the last 10,000 years equal to the approximate volume of surveyed cave. However, many of the caves of the Sierra de El Abra (Ventana Jabalí, Cueva de la Ceiba, Joya de Zimapan, etc.) are deep phreatic caves formed well before the present cycle of erosion. Moreover, the known and surveyed caves are certainly only a very small part of the existing caves; large areas of the range have yet to be visited. Another indication of the antiquity of cavern making in the El Abra is gained from dates of 8,000 and 19,000 years of two relatively recent stalagmite samples (obtained by uranium/thorium dating, Peter Thompson, McMaster University). Thus both the rate of cavern formation and the amount of time involved are much greater than suggested by Harmon. It does appear that of the limestone removed in solution from the Sierra de El Abra, a much greater percentage is derived from the surface than is so derived in most karst areas, as there has been relatively little surface modification.

Reply

Russell S. Harmon [*]

In their discussion of my paper, Fish and Russell have correctly called the attention of readers to some errors, especially in nomenclature; but their major criticism seems to be that the paper does not present a complete picture of the groundwater geochemistry of the El Abra region. In this respect they seem to have overlooked the title of the article, which stressed the preliminary nature of the study. Not all of the Sierra de El Abra springs and certainly not all caves were sampled, and there was no indication or suggestion in the paper to give this impression. The sulfurous and thermal springs were avoided during the preliminary stages of the study because of the added complexities presented by these deep-circulating waters which are not directly related to the primary hydrology and drainage of the Sierra de El Abra karst. That the Nacimiento del Río Frío is located in the Sierra de Guatemala was indicated in the paper (p. 74); it is outside of the El Abra region. These samples and others collected from outside the El Abra region were included in the study to indicate the different chemical characters of waters in the two karst areas.

A second point of criticism raised by Fish and Russell concerned the diagram (Fig. 6, p. 83) indicating seasonal variations in the chemistry of the El Abra waters. The paragraph discussing seasonal variations (p. 81) was introduced by the statement that certain "trends were noted for the sampling periods, **suggesting** an annual cycle in the water chemistry of the region." Because the Sierra de El Abra region has been very intensely karstified internally, there can be little doubt that the flow and chemistry of the springs draining the karst system are subject to rapid fluctuations in response to heavy rainfalls. No correlation between spring discharge and water chemistry was made during the study. Thus, the curves shown in Fig. 6 were intentionally smoothed, dashed, and without data points so as to indicate only maxima, minima, and expected variation in the chemical parameters measured or calculated.

Finally, Fish and Russell have correctly called the attention of readers to an error in the stated denudation rate. The rate of solution should be 25 x 10^3 m^3/yr and not 25 m^3/yr as indicated in the text. This change in the denudation rate figure does thus support the idea that there still exists much undiscovered cave passage in the region. It does not in itself however require that a greater period of time than stated is necessary to account for the cave volume present in the Sierra de El Abra. Although the deep phreatic caves such as Ventana Jabali, Cueva de El Abra, and Joya de Zimapan were admittedly formed during an earlier cycle of erosion, the majority of cave passage associated with the El Abra Limestone is not of this type and is associated with the present cycle of erosion.

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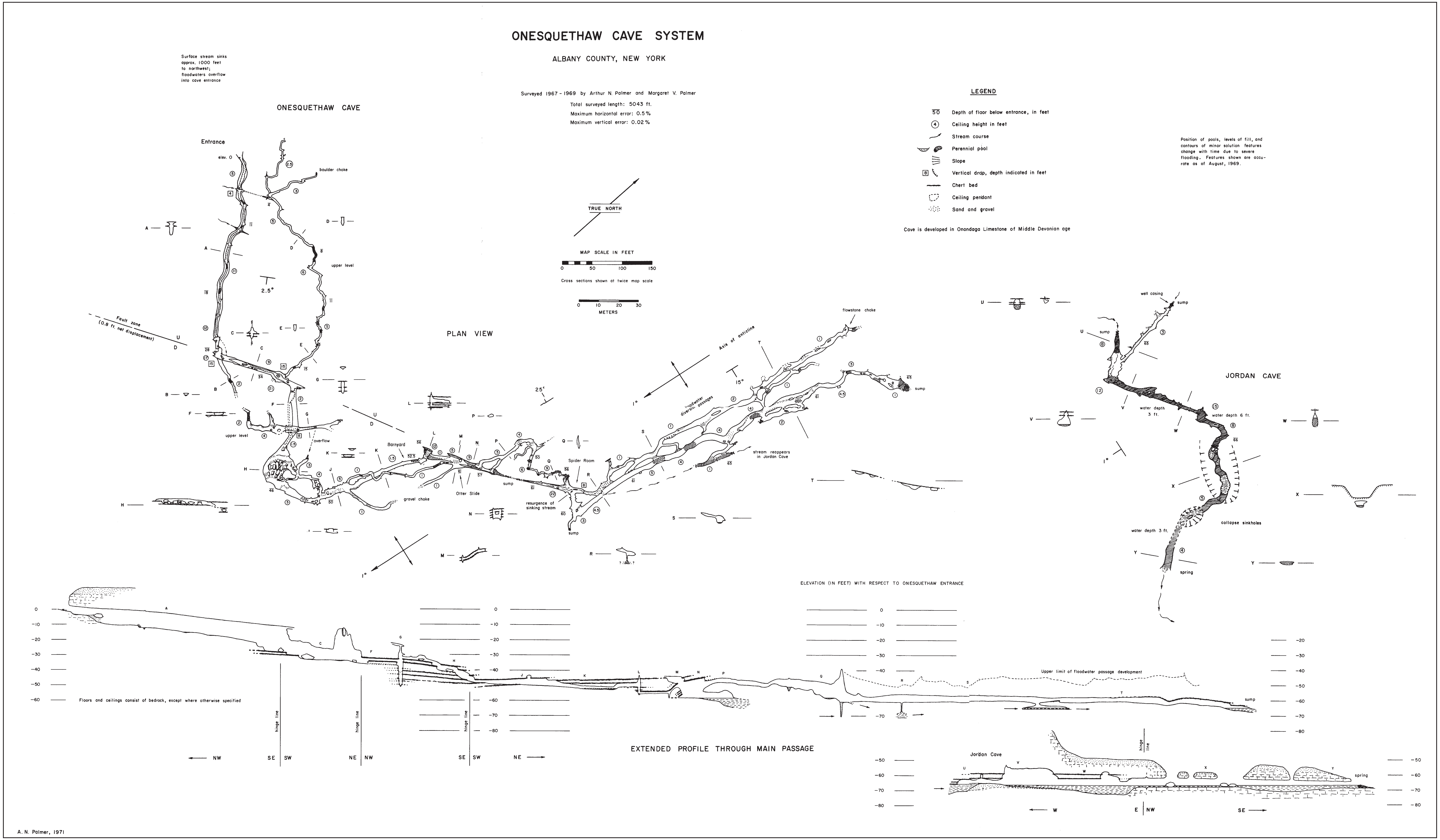

ONESQUETHAW CAVE SYSTEM

ALBANY COUNTY, NEW YORK

Surveyed 1967 - 1969 by Arthur N. Palmer and Margaret V. Palmer
Total surveyed length: 5043 ft.
Maximum horizontal error: 0.5 %
Maximum vertical error: 0.02 %

LEGEND

- $\overline{50}$ Depth of floor below entrance, in feet
- ④ Ceiling height in feet
- Stream course
- Perennial pool
- Slope
- $\boxed{8}$ Vertical drop, depth indicated in feet
- Chert bed
- Ceiling pendant
- Sand and gravel

Cave is developed in Onondaga Limestone of Middle Devonian age

Position of pools, levels of fill, and contours of minor solution features change with time due to severe flooding. Features shown are accurate as of August, 1969.

Surface stream sinks approx. 1000 feet to northwest; floodwaters overflow into cave entrance

MAP SCALE IN FEET

Cross sections shown at twice map scale

Floors and ceilings consist of bedrock, except where otherwise specified

A. N. Palmer, 1971